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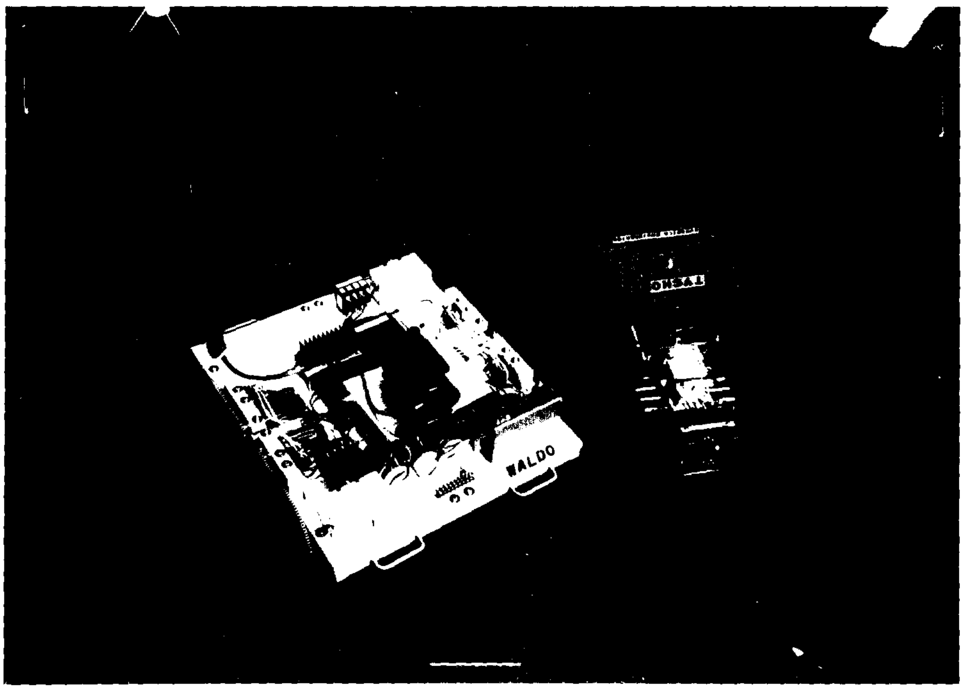
impractical at best to try to eliminate those users from the band, as users are not registered, may have little understanding of the underlying radio issues, and will have little incentive to give up their cordless phones, remote speakers, computer LANs, VCR extenders, burglar alarms, etc. Identifying and locating spread-spectrum interference sources would appear to be a formidable technical challenge, while convincing the user to stop operating the device is an equally


WALDO

Simulated Lunar Teleoperations Project

1. Overview

I have been conducting teleoperations research since 1987, focusing on modeling vehicles that might be used in support of a lunar colony. Tycho, the first generation machine, has been complete since mid-1988, and Waldo, the second generation machine, is Phase One Complete (a very basic teleoperated vehicle). The Tycho project was done in part for the Lunar Society, a volunteer organization promoting manned space exploration and colonization. I have been conducting this research in my spare time, with assistance from numerous people.

2. Introduction

Teleoperation is basically remote control of a device from a separate (usually distant) location. Lunar teleoperation is the remote operation of a vehicle which is on the surface of the moon while the operator is on the Earth. This offers a significant advantage, as the vehicle can be operated 24 hours a day, with no requirement for additional personnel on the moon.

The general case of a lunar teleoperated vehicle is one which can be moved by radio controls (telecommand) and which sends real-time pictures (and other telemetry) back to the operator by means of a video camera and transmitter. Waldo has (or will have) other features, such as a bulldozer blade, a manipulator arm, a stereo camera pair, etc. that allow it to do useful work in support of a lunar colony, or other inhospitable/inaccessible environment.

3. Motivation

3.1. Low Support Costs

The cost of supporting each person in a lunar colony is expected to be very high. Getting any mass to the moon will be very expensive, and the high price to import any expendable or consumable items such as air, water, and food will cause these ongoing costs to be a significant factor in the operation of a lunar

3.3. Initial Construction

Teleoperated vehicles will be able to do some initial work on the colony before the first colonists arrive, as no life support or initial infrastructure is required. For instance, a number of tasks, like leveling and grading a landing field, digging foundations for the habitat modules, and surveying the colony area could all be completed by the time the first colonists arrive.

3.4. Amplifying Presence

Once the colonists are on site, the teleoperated vehicles will assist them in their construction and other tasks, allowing one on-site colonist to do the work of several with the help of one or more earth-based operators. For instance, a teleoperated vehicle could transport supplies, supply electrical power, pick up dropped tools, and assist in assembly and construction work.

3.5. Mining

Teleoperations can also be used for mining the lunar regolith, in support of either the mining operations of a colony or an automated mine. Lunar regolith contains oxygen, aluminum, and other valuable raw materials that can be recovered, but large amounts of regolith may have to be transported to a central smelting/refining complex.

4. TELEOPERATIONS SIMULATION ISSUES

4.1. Teleop Delay

The most significant feature of lunar teleoperations is the (approximately) 3-second speed-of-light round-trip communications delay. If the operator of a lunar teleoperated vehicle tells it to stop, he will not see the vehicle stop until 3 seconds later. This is the major obstacle to efficient Lunar teleoperations work, and in order to develop command/control systems and train operators, this delay must be effectively modeled.

4.2. On-site Workers

In the real world, there may be colonists working with the vehicle. In this case, there is a 3-second audio communications delay between the Earth-based operators and the lunar workers. This may be modeled with a bucket-brigade analog delay line, ADCs and DACs with computer memory buffers, or other means. At this time there are no plans for modeling this delay, as we are researching vehicle operations without nearby colonists. If such a capability becomes available however, we'll put it to good use.

5. TYCHO

The first generation vehicle was built using radio-control hobbyist equipment originally intended for use in R/C planes and cars. It is named Tycho after the prominent crater on the moon of that name.

6. WALDO

The second generation vehicle is being built using the lessons we learned while building Tycho. Most of them revolve around the theory that *Bigger is Better*, and *Keep It Simple, Stupid*. The name was chosen because it more closely defines the project - a waldo is a remote manipulator used for handling objects at a distance.

6.1. Design Goals

The major problems with Tycho had to do with the small size. Waldo is as large as practical, consistent with moving it through doorways and transporting it in a car. Steering control with Tycho is difficult at best, so the problems of steering and suspension are eliminated at the source. Waldo has four fixed lawn-tractor wheels with independent drive motors, and steering is done by driving the wheels on either side at different speeds (or in opposite directions). An 8031-based microcomputer runs the drive motors, and is commanded through touch-tones or RS-232. Touch-tones are transmitted from a ham radio portable transceiver (HT) and can perform basic movements (forwards, backwards, turns, select speeds). RS-232 commands come from packet radio gear or the main on-board computer, which is expected to be Z-80, 64180, or 68HC11 based. Dual ATV (Amateur TV) transmitters will send separate or stereo TV images back to the operator(s). A bulldozer blade will allow earthmoving experiments, and a manipulator arm will be used for more precise work. Other accessories will be added as time (and budgetary constraints) allow. The original goals of determining operator and control "goodness" remain in effect. Operating time is at least an hour between recharges, and recharge currently happens overnight. A fast-charge, on the order of an hour, is possible, but has not yet been implemented.

6.2. Pending Tasks

The following tasks are those which have not been started or which are otherwise incomplete. They represent a partial list of tasks which are planned to bring the vehicle up to fully functional status:

- Cameras - stereo configurations, mounting and pointing
- Bulldozer blade - mechanical design and fabrication, electrical and computer interface, drive motors, etc.
- Audio delay to simulate on-site workers (optional)
- Operator's console - controls, telemetry displays
- Post-processing - operator and control "goodness"
- Manipulator arm - programming, operator and computer interfaces
- Flux-Gate compass - computer interface and autopilot programming
- Sonar - range-finding, "LORAN" positioning, collision avoidance
- Laser - pointing, position finding
- Batteries - fast and float chargers, state of charge determination
- Base computers - hardware interfaces, lots and lots of software(!)
- Documentation - written, photographic, schematic, CAD.

6.3. Current Design Concepts

The following are our current ideas of how Waldo is going to be configured. They are subject to change at any moment. The two major parts of the project are the vehicle and the base station.

6.3.1. Vehicle

The main constraints on the vehicle are that it be light in weight (two-person carry is our goal), be able to fit through doorways, and be transportable in a VW Golf. With those constraints in mind, it should be as large and sturdy as possible.

The vehicle is a flat platform with four fixed wheels. Differential steering will be used (like a Bobcat), and suspension problems have been eliminated at the source (there is no suspension, the wheels are fixed to the chassis).

Chassis: The frame is made of 1.25-inch square aluminum "U" channel bolted together. Solid aluminum blocks are used at the corners to provide strength and prevent the bolts from collapsing the channels. The frame is 29.5 inches long and 25 inches wide, with a single stiffener in the middle between the wheels. Additional solid blocks are fastened to the bottom of the channels to provide mounting points for the shoulder bolts which function as stub axles. The wheels bring the total width to 36.5 inches.

Drive: The wheels are Wheelhorse garden tractor front wheels with 13x5.00-6 tires, and are chain-driven from modified Makita and Sears cordless drills. Fans have been installed to keep the drive motors cool, as they would otherwise overheat in this application. The vehicle moves about 4.2 feet per second, or 2.8 miles per hour on flat, level concrete. More speed is not desirable, as it leads to less precise control over the vehicle. Worst case, Waldo may move about 12 feet before the operator can react!

Computer: There will be at least two onboard computers, one for the drive subsystem and one to control the rest of the vehicle. The drive subsystem is run by a Micromint RTC-52 single-board computer with assembly language routines to control PWM motor drivers. While this computer has an onboard BASIC interpreter, we found that it couldn't generate the four PWM outputs fast enough.

The main onboard computer has not yet been selected, but may be a Micromint RTC-180, a 64180-based single-board computer. It will control the radios, robot arm, autopilot, plow blade, and other systems. It will be programmed in Z-80 (or 64180) assembly.

Radio: The radio gear operates on the amateur bands, and comprise packet radio command and telemetry links as well as one or two channels of ATV video feedback for the operator. The video channels will be switched between various cameras and other on-board video sources (computer terminal, etc.). The "command" frequency is in the 144 MHz band. This frequency is used for commanding the vehicle through Touch-Tones, and will be the half-duplex packet radio channel for RS-232 control. We will select a frequency in the 450 MHz band for use as the "back channel" when we convert the packet radio link to full duplex. The packet radio link will transmit commands to the vehicle and telemetry back to the base in both half and full duplex modes. The primary ATV channel is in the 915 MHz band, and uses FM TV to avoid the problems inherent in VSB (Vestigial Side Band) or AM TV. The secondary video channel be in another amateur band, depending on the results of testing the 915 MHz gear.

Cameras: The primary camera is a Sony CCD-TR5 8-mm camcorder with wide-angle adapter lens. This camera has auto-focus, power zoom, and overlay capabilities. We will be building a pan/tilt mount for this camera to enable the primary operator to inspect the vehicle and the area around it. This will be supplemented by a stereo pair of tube-type Sony Watchcam cameras for use with the manipulator arm. There may also be "overview" cameras positioned around the work-site to give the operators (and observers) alternate views.

Manipulator Arm: A Heathkit HERO-2000 robot arm modified for battery operation will be mounted on the back of the vehicle facing aft. Assembly of the arm was completed during the beginning of July, 1990. The arm will be used for fine-control experiments. As a final exercise, a teleoperator in training may have to stack glassware with a three-second delay!

Power: Power will be provided by Gates Cyclon lead-acid batteries. Voltage regulators and/or converters will provide other voltages for other subsystems as needed. Separate batteries will be used for drive, computer, arm, and radio gear to prevent interactions. If power to the computers or radio gear fails or drops below certain minimums, all power to the vehicle will be disabled to prevent uncontrolled movement.

The drive battery is four 'BC' cells in series, giving 25 amp-hours at 8 volts to drive the four motors. Since the cordless drill motors are rated to run on 7.2-volt NiCad batteries, this is a good compromise. As the Cyclon cells have a much higher current capacity than the original NiCads, the drive computer will have to monitor currents and limit drive power if a wheel stalls, to prevent motor burnout. Backup over-current protection is provided by ganged 30-amp circuit breakers on the drive motors.

Bulldozer Blade: There will be a blade on the front of Waldo that will allow the operator to do some construction work, such as leveling a landing field, excavating a habitat module foundation, covering a habitat, and so on. Digging in the sand at a beach will be a good test of these skills.

6.3.2. Base Station

The base station is where the operator sits, controls the vehicle, and views the telemetry. The other support personnel also sit here. We hope to be able to make the base reasonably portable, so that we can (for instance) go to a beach and dig in the sand or go to an SF convention and recruit test operators. By monitoring the response of novice operators, we can get a better idea of control "goodness".

6.3.2.1. Computers

There are a number of computers available to us for the Waldo project. Some of them have other tasks, and cannot be dedicated to the project, and more could be obtained if a need is demonstrated for them.

6.3.2.2. Tasks

The base station involves a number of tasks which must be performed simultaneously. This involves either multi-tasking on one or more computers or distributing tasks among multiple CPUs

- Controls Interface
- Delay
- Control of Radio Gear
- Telemetry Display
- Operator Display

All command and telemetry packets are logged to disk with time stamps and comments for post-processing. As with the Tycho project, the Waldo project will have a defined data format for these files so that post-processing can be done off-site. The main purposes of logging and post-processing is to determine operator and control "goodness" and generate ideas for modifications. Video data will be recorded with time stamps, so that a particular mission can be replayed.

6.3.2.3. Personnel

There will be a variable number of people involved in the operation of Waldo. Some people can perform more than one function, and there may be more than one person at any one position. The total number can vary from one (one person performs all functions simultaneously, not recommended!) to five plus any number of observers.

- Vehicle Operator
- Arm Operator
- Supervisor
- Radio Operator
- Safety Officer:
- Observer:

6.3.3. Data Flow

This section covers the general flow of data through the base station and vehicle. It is not presented as a precise representation of the configuration of the two systems, as such details are not yet defined, but as more of an overview of how things work. Keep in mind that the specifics of which computer performs which task are unknown and therefore subject to change at any moment...

There are two types of data that flow through the system, command and telemetry. Command data is comprised of everything coming from the base and destined for the vehicle, telling the vehicle and it's subsystems what to do, while telemetry is all data gathered at the vehicle destined for display at the base. While it is strictly speaking a form of telemetry, the video signals from the vehicle are not included in this discussion, as they are not computer data. Video signals are merely displayed in real-time (with the appropriate Heads Up Display overlays) as they are received, and logged to videotape.

For a more complete documentation package, other information or to assist, please contact:

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